

The Dynamics of Tropical Cyclones

Roger K. Smith
Meteorological Institute
University of Munich
Theresienstr. 37, 80333 Munich, Germany
phone +49 (89) 2180-4383 fax +49 (89) 2180-4182 email roger@meteo.physik.uni-muenchen.de

Award #: N000149510394
<http://www.meteo.physik.uni-muenchen.de>

LONG-TERM GOALS

The broad objectives of this research effort are to better understand the mechanisms that determine tropical cyclone motion, structure, and intensity change and to apply the new knowledge to improving tropical cyclone forecasts.

OBJECTIVES

The specific objectives of the current effort are:

1. To continue our study of the dynamics of the extra-tropical transition of tropical cyclones with emphasis on idealized modelling;
2. To continue our diagnosis of hurricane track and intensity change as predicted by the Geophysical Fluid Dynamics Laboratory (GFDL) model using the technique of potential vorticity inversion;
3. To continue our investigations of tropical-cyclone - trough interaction;
4. To continue a study of the factors which govern the size of tropical cyclones and the mechanisms involved in the generation of midlevel typhoons;
5. To continue an idealized numerical modeling study of hurricane - ocean interaction.
6. To initiate a comparative study of hurricane growth in various numerical models with the same idealized configuration;
7. To initiate a study of the mechanisms responsible for inner-core asymmetries in environmental vertical shear;
8. To continue the development and improvement of methods for (a) the implementation of synthetic tropical cyclones in global and regional operational prediction models and (b) the initialization of tropical-cyclone ensemble forecast models;
9. To continue the development, testing and further improvement of the Statistical Ensemble Prediction System STEPS for the track and intensity of tropical-cyclones;
10. To continue the process of operational implementation of the barotropic hurricane track prediction model WBAR in the U. S. Navy's Automated Tropical Cyclone Forecasting system ATCF and its improvement;

Report Documentation Page			Form Approved OMB No. 0704-0188		
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 30 SEP 2002		2. REPORT TYPE		3. DATES COVERED 00-00-2002 to 00-00-2002	
4. TITLE AND SUBTITLE The Dynamics of Tropical Cyclones				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Meteorological Institute,,University of Munich,Theresienstr. 37, 80333 Munich, Germany, , ,				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT The broad objectives of this research effort are to better understand the mechanisms that determine tropical cyclone motion, structure, and intensity change and to apply the new knowledge to improving tropical cyclone forecasts.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 9	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

11.To initiate the development of a combination of an ensemble version of WBAR and the hurricane intensity prediction model of K. Emanuel of the Massachusetts Institute of Technology MIT;

12.To initiate a study for the development of new concepts for the construction of synthetic storms in numerical prediction models on the basis of a statistical analysis using a very large number of base dates/times of tropical-cyclone events (811) in analyses and predictions of the year 2001 of the U. S. Navy's Operational Global Atmospheric Prediction System NOGAPS.

APPROACH

The approach involves a mix of analytic and numerical model calculations, as well as the analysis of operational and field data. Recent findings from theoretical studies are being applied to the problem of initializing tropical cyclones in numerical forecast models. Group members in addition to the PI include: Drs. Sarah Jones (working on the effects of vertical shear on vortex evolution with diplom student Mr. Richard Patra and on the extra-tropical transition of tropical cyclones with doctoral student, Ms. Helga Weindl); Dominique Möller, (working on diagnosing hurricane track and intensity changes as predicted by the GFDL model); Maria Peristeri (working on a modelling study of midget typhoons); Lloyd Shapiro (working on potential vorticity asymmetries and tropical cyclone evolution), Wolfgang Ulrich and Hongyan Zhu (working on the development of an idealized coupled hurricane - ocean model), and Harry Weber (working on topics related to operational tropical-cyclone track and intensity prediction). The PI is working with doctoral students, Ms. Seoleun Shin on a study of tropical-cyclone genesis and Mr. Sang Nguyen on a comparative study of hurricane growth in a variety of model configurations.

WORK COMPLETED

The following papers have been accepted for publication or have appeared in print: Möller and Shapiro (2002), which uses forecasts from the GFDL hurricane model to diagnose the symmetric and asymmetric influences on the structure and intensity of Hurricane Opal of 1995; Nguyen et al. (2002), which uses an axisymmetric version of the minimal three-dimensional hurricane model of Zhu *et al.* (2001) to study various fundamental aspects of hurricane dynamics; Smith (2002), which describes a simple slab model for the hurricane boundary layer; Zhu and Smith (2002a), which uses the Zhu *et al.* model to investigate the importance of three physical processes on tropical cyclone evolution; Zhu and Smith (2002b), which examines a new version of the model reformulated with a Charney-Phillips grid (CP-grid) in the vertical instead of the original Lorenz grid (L-grid); Ulrich *et al.* (2002), which examines the difference between the evolution of a hurricane-like vortex in an axisymmetric model and that of an inter-tropical convergence-zone-like disturbance in a slab-symmetric model, starting from an initial disturbance with the same lateral structure; Weber (2001), on the barotropic hurricane track prediction system WBAR; Weber (2002), on the statistical hurricane track prediction model STEPS. A revised version of the review paper on the extratropical transition of tropical cyclones has been completed (Jones *et al.*, 2002).

Further development of the coupled ocean - hurricane model has been carried out and the model is being used for basic studies of ocean feedback effects on hurricane evolution, including the effects of asymmetric processes.

The revised initialization method of the Australian Bureau of Meteorology Research Centre's (BMRC) regional tropical-cyclone prediction model TC-LAPS (cf. Davidson and Weber, 2000) has been implemented successfully together with N. Davidson and tests under semi-operational conditions are nearly finished. Together with C. Sampson and J. Goerss of the Naval Research Laboratory (NRL), WBAR has been implemented successfully in the U. S. Navy's ATCF system and is currently being tested semi-operationally. The same model has been implemented at the Geophysical Service of the German Army (AWG) together with T. Prenosil on the basis of data sets from the global GME model of the German Weather Service (DWD).

RESULTS

Calculations with the minimal hurricane model using the L-grid show evidence that a computational mode in temperature is excited during the period of rapid vortex intensification, which begins when grid-scale latent heat release occurs in the core region. Thus it would appear that the solution in the mature stage of evolution is contaminated by this mode. The mode does not occur in calculations with the CP-grid. We have shown also that the vortex asymmetries that develop during the mature hurricane stage are sensitive to the choice of vertical grid and argue that those that occur in the CP-grid formulation are more realistic. It is possible that the computational mode is a spurious feature of many earlier studies of asymmetries in hurricane models in which moist processes are represented, especially in models with limited vertical resolution.

Recent calculations using the simple hurricane boundary layer model have indicated the need to represent the mixing effects of shallow convection in order to produce a realistic radial distribution of boundary layer humidity. Significant for hurricane dynamics is the fact that the radial profiles of boundary layer equivalent potential temperature, θ_{eb} , and surface latent heat flux in the inner core region are relatively insensitive to the outer wind profile (Fig. 1). To a first approximation the θ_{eb} determines the virtual temperature distribution above the boundary layer in regions of cloud.

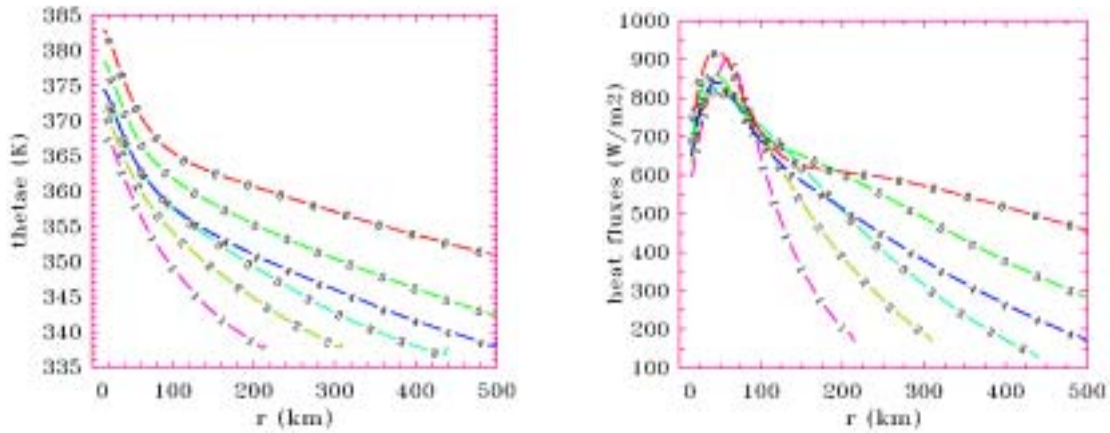


Figure 1. Radial profiles of equivalent potential temperature, θ_e , (left panel) and surface latent heat flux (right panel) in the simple hurricane boundary layer model of Smith (2002). Numbers on curves relate to different radial profiles of tangential wind speed above the boundary layer. These profiles have the same maximum tangential wind speed (40 m s^{-1}), which occurs at the same radius (50 km), but the profile width increases with the number on the curve.

In Möller and Shapiro (2002) we diagnosed the balanced contributions to the intensification of Hurricane Opal of 1995 to evaluate the impact of heating and friction as well as eddy fluxes on the storm. At the time of the analysis, during a period of rapid intensification, asymmetric eddy forcing made a small contribution to Opal's lower-tropospheric near-core spinup. Thus, on face value, this study supports the conclusion that an upper-level trough was not important to the intensification of Opal. As noted in our study, however, the technique of piecewise PV inversion is required in order to isolate the contribution of the trough by itself. This technique has been implemented in our most recent investigation, which is the first to use the method of piecewise PV inversion to diagnose the asymmetric features that contribute to tropical cyclone intensification. It is found that the eddy fluxes associated with a PV anomaly are not locally confined to the region of the anomaly. Though the upper-level trough is an outer environmental feature, its influence is found to extend into Opal's inner-core region. The eddies associated with the trough induce an upper-level inner-core acceleration. There is no indication from the present diagnosis that the upper-level trough was a significant contributor to Opal's lower-tropospheric intensification.

In the coupled hurricane – ocean model, the ocean feedback is negligible during the gestation period of the initial vortex and is negative during the mature stage, compared with a case in which the sea-surface temperature is held constant at its initial value. The key sensitivity comes with the translation of the hurricane. Although a cooling of up to several degrees is found in the calculations, the region of coldest sea-surface temperatures lags more than one radius of maximum winds behind the actual centre position of a poleward and westward moving hurricane on a beta-plane, and is thus less effective in limiting the hurricane strength than one might expect. Calculations indicate that the negative feedback is comparable in strength to a run with a constant, but half a degree lower sea-surface temperature. The type of mixing parameterization applied in the ocean's mixed layer has a significant effect on the extent of the region where the sea-surface temperature is lowered; however there is only a minor difference in the calculated depths of the mixed layer.

We have carried out idealised modelling studies on the extratropical transition of tropical cyclones. Firstly, we have initiated a study of the interaction of a tropical-cyclone-like vortex and a front using a barotropic model, in which the front is represented as a discontinuity of vorticity. Preliminary results of this study show that the vortex excites a wave on the front. The circulation associated with the frontal wave steers the vortex, with the result that the vortex moves away from a surface front, but towards a tropopause front. The results are sensitive to the radial structure of the vortex, such that if the tangential wind decreases more slowly with radius the interaction is stronger. On a β -plane, Rossby waves propagate from the vortex towards the front and modify the structure of the front. Secondly, calculations of the interaction of a tropical-cyclone-like vortex and a baroclinic wave in a three-dimensional numerical model show that the relative motion of the vortex and the baroclinic wave is influenced by the mid-tropospheric potential vorticity gradient associated with the mid-latitude flow. In turn, the evolution of the mid-latitude flow is influenced by the presence of the tropical-cyclone-like vortex. The vortex can act as an initial perturbation, which releases the baroclinic instability present in mid-latitudes. The interaction between the vortex and the baroclinic wave is very sensitive to their relative locations.

Together with K. Puri of BMRC and based on the experiments of Puri et al. (2001), a method for the initialization of an ensemble version of TC-LAPS has been developed. First tests of the new method under variation of the initial storm position, translation velocity and outer structure have been

successful with regard to the spread of forecasts and the location of observed tracks inside the predicted ensemble envelopes.

IMPACT/APPLICATIONS

The semi-operational tests and the further improvement of the barotropic model WBAR, on the basis of a very large number (811 TC events) of NOGAPS analyses and forecasts, and the planned operational-ization of a complete track and intensity prediction version of STEPS in the ATCF system in cooperation with J. Goerss and C. Sampson of NRL, may have a positive effect on the operational prediction of tropical cyclones. An ATCF-version of STEPS would also include a graphical interface of its probabilistic predictions. The development of such an interface is being considered in cooperation with P. Harr of the Naval Postgraduate School (NPS).

The very large number of NOGAPS analyses and predictions mentioned above can be used for the development of new concepts for the construction of synthetic storms in numerical prediction models. The statistical analyses will focus inter alia on the structure of tropical cyclones undergoing extratropical transition and on an improvement of the method to adjust cross-storm flow contributions to observed storm translation velocities in numerical models (cf. Weber and Smith, 2000, and Davidson and Weber, 2000).

The planned coupling of an ensemble version of WBAR with the intensity prediction model of Emanuel (1995), carried out in close cooperation with K. Emanuel of the MIT, may have a positive impact on future tropical-cyclone track and intensity prediction. First tests of an ensemble variant of WBAR, varying the depth of its initial Deep-Layer-Mean fields, showed quite spectacular results so far. First, the intensity model will predict the intensity of a given storm in dependence on positions predicted by a WBAR ensemble, while later, the intensity model will be implemented in WBAR, allowing the model storm to vary in strength and to modify the storm's track during a model forecast. The three-dimensional three-layer hurricane model has the potential to improve our understanding of the dynamics of hurricane behaviour. Its coupling with the two-layer ocean model is expected to enhance our understanding of ocean feedback on hurricanes.

TRANSITIONS

It is expected that the revised vortex enhancement method for TC-LAPS will be used operationally at BMRC during the next Australian tropical-cyclone season 2002/2003. The use of the above method in the DWD's global model GME is subject of current work with T. Prenosil of AWG. The new initialization method for the TC-LAPS ensemble prediction system is being tested intensively together with K. Puri and N. Davidson of BMRC with the aim of an operationalization of this model.

The barotropic track prediction system WBAR is being tested semi-operationally in the ATCF system under the surveillance of C. Sampson of NRL. The WBAR model has been implemented also for operational use at AWG together with T. Prenosil and is presently being tested there under semi-operational conditions.

RELATED PROJECTS

The review of buoyancy is being carried out in collaboration with Dr. M. Montgomery (Colorado State University) and that on the factors that govern the size of tropical cyclones is with Ms. Nguyen Chi Mai (Vietnamese National Centre for Hydrometeorological Forecasting). Sarah Jones is collaborating with Dr. C. Thorncroft (SUNY, Albany), Dr. P. Harr (NPS), Dr. M. Jukes (University of Oxford), and Dr. E. Ritchie (University of New Mexico). Dominique Möller and Lloyd Shapiro are collaborating with Dr. Robert Tuleya of the Geophysical Fluid Dynamics Laboratory. Harry Weber is collaborating with Dr. J. Goerss (NRL), Drs. N. Davidson and K. Puri (BMRC), Dr. K. Emanuel (MIT), Dr. P. Harr (NPS), Mr. D. Majewski (DWD), Dr. T. Prenosil (AWG), Ms. Do Le Thuy and Ms. Nguyen Thi Minh Phuong (Vietnamese Hydrometeorological Service), and with Drs. Kieu Thi Xin and Phan Van Tan (Hanoi University of Science).

REFERENCES

Davidson, N. E., and H. C. Weber, 2000: The BMRC high-resolution tropical cyclone prediction system: TC-LAPS. *Mon. Wea. Rev.*, **128**, 1245-1265.

Emanuel, K. A., 1995: The behavior of a simple hurricane model using a convective scheme based on subcloud-layer entropy equilibrium. *J. Atmos. Sci.* **52**, 3960-3968.

Goerss, J. S., 2000: Tropical cyclone track forecasts using an ensemble of dynamical models. *Mon. Wea. Rev.* **128**, 1187-1193.

Puri, K., J. Barkmeijer and T. N. Palmer, 2001: Ensemble prediction of tropical cyclones using targeted diabatic singular vectors. *Quart. J. Roy. Met. Soc.*, **127**, 709-731.

Weber, H. C., 2001: Hurricane track prediction with a new barotropic model. *Mon. Wea. Rev.*, **129**, 1834-1858.

Weber, H. C., and R. K. Smith, 2000: A monsoon depression over northwestern Australia. Part III: Motion. *Aust. Meteor. Mag.*, **49**, 1-21.

Zhu, H., R. K. Smith, and W. Ulrich, 2001: A minimal three-dimensional tropical cyclone model. *J. Atmos. Sci.*, **58**, 1924-1944.

PUBLICATIONS

Jones, S. C., P. A. Harr, J. Abraham, L. F. Bosart, P. J. Bowyer, J. L. Evans, D. E. Hanley, B. Hanstrum, R. E. Hart, F. Lalaurette, M. R. Sinclair, R. K. Smith, and C. D. Thorncroft: The extratropical transition of tropical cyclones: forecasting challenges, current understanding and future directions. Revised version returned to *Wea. Forecasting*.

Möller J. D., and L. J. Shapiro, 2002: Balanced contributions to the intensification of Hurricane Opal as diagnosed from a GFDL model forecast. *Mon. Wea. Rev.*, **130**, 1866-1881.

Nguyen, C. M., R. K. Smith, H. Zhu, and W. Ulrich, 2002: A minimal axisymmetric hurricane model. *Quart. J. Roy. Meteor. Soc.*, **128**, (in press)

Shapiro, L. J., and J. D. Möller, 2002: Influence of atmospheric asymmetries on the intensification of Hurricane Opal: Piecewise PV inversion diagnosis of a GFDL model forecast. Submitted to *Mon. Wea. Rev.*

Smith, R. K., 2002: A simple model of hurricane boundary layer. *Quart. J. Roy Met. Soc.* (in press).

Ulrich, W., R. K. Smith and Nguyen, C. M., 2002: Comparison of an axisymmetric hurricane model with the corresponding slab-symmetric ITCZ model. *Quart. J. Roy. Meteor. Soc.*, **128**, (in press).

Weber, H. C., 2002: Hurricane track prediction using a statistical ensemble of numerical models. *Mon. Wea. Rev.* (in press).

Zhu, H., and R. K. Smith, 2002a: The importance of three physical processes in a three-dimensional tropical cyclone model. *J. Atmos. Sci.*, **59**, 1825-1840.

Zhu, H., and R. K. Smith, 2002b: Effects of vertical differencing in a minimal hurricane model. *Quart. J. Roy. Meteor. Soc.* (in press).

Conference papers:

The following invited paper was presented at the 40th Anniversary meeting of the DLR Institute of Atmospheric Physics, Oberpfaffenhofen, Germany, July 2002:

Smith, R. K., Die Dynamik tropischer Wirbelstürme (The dynamics of hurricanes).

The following 10 papers were presented at the 25th AMS Conference on Hurricanes and Tropical Meteorology held in San Diego, April/May 2002

Jones, S. C. and E. A. Ritchie, The development of asymmetric vertical motion in idealised tropical cyclones under the influence of vertical shear.

Juckes, M. and S. C. Jones, The interaction of a tropical-cyclone-like vortex and a front in a barotropic model.

Möller, J. D., and L. J. Shapiro, Symmetric and asymmetric contributions to the intensification of Hurricane Opal in a GFDL model forecast.

Puri, K., J. Barkmeijer, N. E. Davidson and H. C. Weber: Ensemble prediction of tropical cyclones.

Shapiro, L. J. and J. D. Möller, Influence of atmospheric asymmetries on the intensification of Hurricane Opal: piecewise PV inversion diagnosis of a GFDL model forecast.

Smith, R. K. A simple model for the hurricane boundary layer.

Ulrich, W., A minimal hurricane model with a coupled mixed layer ocean.

Weber, H. C., Hurricane track and intensity prediction using a statistical ensemble of numerical models.

Weindl, H., Numerical experiments on the interaction of a hurricane-like vortex with a baroclinic wave.

Zhu, H., Effects of vertical differencing in a minimal hurricane model.

Theses

Hongyan Zhu, 2002: A minimum tropical cyclone model. Dr. rer. nat. (University of Munich)